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ON POSITIVE AND NEGATIVE ELECTRONS.

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The illustrious founder of our society will forever occupy a prominent place in the history of physical science, not only for his experimental researches in electricity and his invention of the lightning rod, but also for his theoretical views. Franklin tried to explain all electrical phenomena that were known in his time by means of a single electric fluid, which he supposed to be present in certain definite quantities in all ponderable bodies, when in their natural or unelectrified state, and in larger or smaller quantities in positively or negatively charged bodies. The rival doctrine was of two electric fluids, which in the days before Maxwell served as the foundation of the mathematical theory of electricity and which was adopted by those physicists who, like Riemann, Weber and Clausius, sought to account for electrostatic and electrodynamic phenomena by one fundamental law for the mutual action of electric particles.

Some twenty-five years ago the relative merits of the different laws of this kind that had been proposed, especially of those of Weber and Clausius, were examined by many physicists and in connection with this, there was much discussion about the motion of the two electricities in an electric current. Whereas, in the applications of Weber's law, they were generally supposed to travel in opposite directions with equal velocities, Clausius could free himself from this restriction, and could even suppose one of the electricities to have no motion at all.

These questions, after having for a time lost much of their interest by the universal spreading of Maxwell's ideas, have again sprung up, and have even become of fundamental importance in the modern theory of electrons. I should therefore like to call attention to them for a few moments, hoping the subject will be thought suitable on the present occasion, because it is somewhat like the old question whether one had to assume Franklin's single fluid or a positive and a negative electricity.

In order to show the connection I may observe that we can never wholly escape from the dualism, the notion of two things with opposite properties, that is forced upon our minds as soon as we come to study phenomena. Indeed, while recognizing but one electricity, the unitarian theory invested ordinary matter with the properties of the missing fluid. It was obliged to assume the existence of a mutual repulsion, not only between the particles of electricity, but also between those of matter and to add to these forces an attraction between a particle of matter and one of electricity. This is not very different from a two-fluids theory; it is even practically equivalent to it, if one of the two fluids is supposed to be permanently fixed to the ponderable matter. After all, we shall have to choose, not, strictly speaking, between one or two electricities, but between one or two *movable* electricities, in modern terms, between one or two kinds of *movable* electrons.

I shall confine myself to the case of metallic bodies and I shall first speak of a phenomenon which at first sight might seem sufficient to lead us to a decision.

Let us consider a very thin rectangular sheet of metal, traversed in the direction of its length, say from left to right, by an electric current, and placed in a magnetic field whose lines of force are perpendicular to the sheet. Let us first suppose the current to consist of a flow of positive electrons, towards the right-hand side, of course. Then, by a well-known rule, each of these electrons will be acted on by a force due to the magnetic field and perpendicular both to the lines of force and to the current. This force will tend to drive the electrons in the direction of the breadth from one edge of the plate towards the other, so that, if two points of these edges, which would be at equal potentials in the absence of a magnetic field, are connected by a conducting wire, a current will be set up in the latter. A similar effect, but in the opposite direction, would be produced if the current were a flow of negative electrons. This is easily seen if we keep in mind that the motion of the negative particles must be supposed to be opposite to the nominal direction of the current and that the force exerted by a magnetic field on a moving electron remains the same if the sign of the charge and the direction of the motion are reversed at the same time. On account of their motion from right to left, the negative particles will therefore be driven towards the same edge of the sheet as the positive ones in the former case; the direction of the current produced in the connecting wire will therefore be reversed.

Having got thus far, we can also see what effect will be caused by the magnetic field if the current we send through the metallic sheet consists of a flow of both positive and negative particles in opposite directions, so that its intensity can be considered as the sum of those of two partial currents, i_1 and i_2. We shall then have a superposition of two opposite effects, either of which may predominate, according to the relative magnitudes of i_1 and i_2.

Now the phenomenon which the foregoing reasoning might lead us to expect, has really been observed. I need scarcely tell you that it was discovered by Professor Hall, then working in the laboratory of the Johns Hopkins University, at a time when there was hardly any question of a theory of electrons. The effect has been investigated for a large number of metals and has been found to have different directions in different substances. This is of especial importance in our discussion, for it seems to prove that we must indeed imagine two kinds of free electrons, the motion of the positive ones predominating in one body and that of the negative ones in the other.

I shall now point out some difficulties which present themselves in the further development of this conception of an electric current as a double stream of electrons. Take for instance the simple case of a current flowing across the junction of two pieces of different metals M and M', say from the former towards the latter. Considering two sections, S and S', of the two metals quite near their surface of separation, I shall denote by n_1 the number of positive particles traveling across S per unit of time in the nominal direction of the current, by n_2 that of the negative ones going the other way, and by n_1', n_2' the corresponding numbers for the section S'. Then, if for the sake of simplicity we suppose all electrons to have equal charges, we shall have

$$n_1 + n_2 = n_1' + n_2',$$

but of course this does not imply that n_1 and n_2 are separately equal to n_1' and n_2'. If the Hall-effect is not the same in the two substances, the ratio between n_1 and n_2 will be different from that between n_1' and n_2'; it may very well be that n_1 is much larger than n_2 and n_1' much smaller than n_2'.

In order to fix our ideas, I shall suppose

$$n_1 > n_1', \quad n_2' > n_2.$$

This means that the number of positive electrons entering the space between S and S' through the first of these sections exceeds the number leaving it through the second, so that the number contained within the space will increase by $n_1 - n_1'$. As there will be an equal increase $n_2' - n_2$ of the number of negative particles the result is a continual accumulation at the junction itself of equal positive and negative charges, or, as we may say, of *neutral* electricity. Conversely, neutral electricity would continually be carried away from the place of contact, if the direction of the current were reversed.

It is further to be noticed that a change in the distribution of neutral electricity would even occur if we had no current at all; if there were two kinds of movable electrons, it would already arise from the causes which produce the phenomenon of contact electricity. As to these causes several hypotheses have been put forth, of which two may be briefly mentioned. In his celebrated paper on the conservation of energy, Helmholtz accounted for the difference of potential between two metals by means of certain attractive forces exerted at very small distances by the material atoms on the particles of the electric fluids, or, as we are to say now-a-days, on the electrons; if, for instance, the positive particles are more attracted by the metal M' than by M, this will of course tend to produce a positive charge of the first metal. A wholly different explanation that has been proposed by Riecke and Drude is based on the assumption that the free electrons in a metal have their share in the molecular agitation by which we account for the phenomena of heat, going to and fro with velocities whose magnitude is a function of the temperature. The consequence of this heat-motion must be a certain equalization of the density (measured by the number of particles per unit volume) with which the electrons are distributed over adjacent parts of space. Hence, if at the same temperature the metal M contains a larger quantity of free positive electrons than M', the first metal will lose and the second will gain a certain number of them and the potential of M' will be made to exceed that of M.

We need not stop to consider in detail these theories; it will suffice to observe that, according to both, the causes which bring about the difference of potential are confined to a very thin layer near the surface of separation of the two metals. Now, whatever may take place in this layer, it is clear that the transfer of electrons from one body to the other will go on until the causes determining it are balanced by the difference of potential that is established. A state of equilibrium would soon be reached in this way if there were but one kind of free electrons. But if there are two, the case will be different. The causes by which the positive electrons are driven across the junction being quite distinct from those on which the flow of the negative particles depends, the value P of the difference of potential which is necessary for preventing a further transfer of the positive electricity will in general differ from the value Q that is required for stopping the current of negative electrons. Hence, as there is but one difference of potential, a true state of equilibrium can never exist, unless there be some other process that has not as yet been taken into account. The only state of things that could be attained by the motion of the particles we are now considering would be one in which the difference of potential has such a value, intermediate between P and Q, that the two kinds of electrons flow in equal numbers towards the same side. It would be a final state inasmuch as there would be no further change in the charges or the potentials, but could not be called a state of equilibrium because there would be a never-ceasing stream of neutral electricity.

The question now arises, in this as well as in our first instance, what will become of the accumulating neutral electricity? We cannot suppose this mixture or combination of positive and negative electrons to be absolutely nothing, so that it might be drawn from a body or heaped up in it for hours or days without any observable change in its properties. We are therefore compelled to imagine some new process by which the neutral electricity is carried back from the places where both positive and negative electrons are concentrated towards those from which they are traveling away. Moreover, it is easily understood that a hypothesis of this kind can only suit our purpose if the moving neutral electricity is *not* composed of free electrons. If it were, all sections of the metallic system would after all be traversed by the same number of positive particles and also by the same number of negative ones and this is precisely what we have begun by denying. Our conclusion must be that the neutral electricity is to be regarded as a real combination, in pairs for instance, of positive and negative electrons, a combination that is formed in one part of the system and is decomposed again in another part towards which it is carried by a kind of diffusion.

Though this is rather complicated, we could be ready to admit it, if in doing so, we could obtain a quite satisfactory theory. Unfortunately, this is by no means the case, for it can easily be shown that the state of things we have now imagined would be in contradiction with the second law of thermodynamics. Indeed, it may be taken for granted that combination of a positive and a negative electron will produce a certain amount of heat and that, conversely, heat will be absorbed if the electrons are separated from each other. If now, as we have been led to assume, neutral electricity were built up in one of two metals which are in contact with each other and decomposed in the other, heat would be continually developed in the first and consumed in the second body. By Carnot's principle this can never be the case in a system that is kept at a constant uniform temperature, as our two metals may be.

If I am right in making this last remark, and if it cannot be invalidated by some new hypothesis, we need no longer continue our comparison of the two theories; we ought surely to give up all attempts to explain phenomena by the assumption of two kinds of movable electrons. I shall only adduce one argument more, which may be drawn from what is known of the so-called canal rays and the α rays of radioactive bodies. The positive electrons which constitute these rays have been found to have a mass of the same order of magnitude as that of the chemical atoms, a fact which lends a strong support to the view that in a metal the positive charges are rigidly fixed to the material atoms and that only the negative electrons can freely move over considerable distances.

As to the Hall-effect, which at first sight seemed to speak so strongly in favor of the two fluids theory, we shall have to examine whether it cannot be accounted for by the motion of negative electrons only. If we succeed in this, as perhaps we can by going somewhat deeper into the mechanism of the phenomenon than we have done in our somewhat superficial discussion of it, we shall after all come to a system of explanations much resembling Franklin's unitarian theory of electricity.

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